SCANNING MIRROR

FIELD OF THE DISCLOSED TECHNIQUE

The disclosed technique relates to optical devices in general, and to a system and method to provide non-sinusoidal oscillatory motion to a scanner, in particular.

BACKGROUND OF THE DISCLOSED TECHNIQUE

Oscillating mirrors are employed to scan objects and raster-scan displays. Such a mirror is generally connected to two vibrating flexural beams, thereby forming a single degree-of-freedom (DOF) structure, wherein the structure has a single torsional resonance frequency. Such scanners oscillate according to a sinusoidal waveform. The high gain (i.e., large compliances) which is exhibited by a second order system at its natural frequency (when there is a small amount of damping), gives rise to a significant angular deflection under a moderate sinusoidal torque.

Sinusoidal motion of the mirror reflects the light beam in a non-uniform manner, thereby yielding non-uniform intensity and hence, a low level of performance. It is possible to improve the scanning performance, if the mirror oscillates according to a triangular waveform. However, the value of the torque which is to be applied to the mirror in order to provide oscillatory motion having the triangular waveform, is approximately two orders of magnitude greater than in the case of

sinusoidal motion. In large scale applications, where large torques can be produced, it is possible to produce this additional torque. However in small scale applications, such as micro-electromechanical systems (MEMS), due to the inherently small dimensions and the limitation of the commonly used electrostatic excitation, it is much more difficult to provide the needed torque.

SUMMARY OF THE DISCLOSED TECHNIQUE

It is an object of the disclosed technique to provide a novel method and system for oscillating the mirror of a scanner according to a geometric-waveform.

In accordance with the disclosed technique, there is thus provided a geometric-waveform oscillator for processing light. The geometric-waveform oscillator includes a plurality of masses, at least one force producing element, and a plurality of elastic elements. Each of the force producing elements is coupled with a respective one of the masses. At least one of the masses includes a light processing module. Each of the force producing elements applies a force to the masses. The elastic elements couple the masses together and the masses with a respective support. The mass values of the masses, the force values of the forces, and the stiffness coefficients of the elastic elements, are selected such that the light processing module oscillates according to the geometric-waveform.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosed technique will be understood and appreciated more fully from the following detailed description taken in conjunction with the drawings in which:

Figure 1 is a schematic illustration of a scanner, constructed and operative in accordance with an embodiment of the disclosed technique;

Figure 2 is a schematic illustration of a five degree of freedom mathematical model of a system similar to the system of Figure 1;

Figure 3 is a schematic illustration of a micro-electromechanical-based system similar to the system of Figure 1; and

Figure 4A is a schematic illustration of a plot of a frequency response of the mirror of the system of Figure 3;

Figure 4B is a schematic illustration of a plot of oscillations of the mirror of the system of Figure 3 as a function of time;

Figure 5 is a schematic illustration of a scanner, constructed and operative in accordance with another embodiment of the disclosed technique.

Figure 6A is a schematic illustration of a packaged device generally referenced 280, including a plurality of the scanners of Figure 1, constructed and operative in accordance with a further embodiment of the disclosed technique; and

Figure 6B is a schematic illustration of a broken section of a scanning MEMS of the packaged device of Figure 6A.

DETAILED DESCRIPTION OF THE EMBODIMENTS

The disclosed technique overcomes the disadvantages of the prior art by providing a multi-degree-of-freedom system, wherein one of whose elements (e.g., a mirror, a directional radiation source, a directional sensor) oscillates according to a triangular waveform. The individual masses of the system, the stiffness coefficients of the elastic elements of the system, and the waveform of the force which excites the system are selected, such that the mirror oscillates according to the triangular waveform. In the description herein below, the term "mass" is used to specify both a physical object and the weight of the physical object.

Reference is now made to Figure 1, which is a schematic illustration of a scanner, generally referenced 100, constructed and operative in accordance with an embodiment of the disclosed technique. Scanner 100 includes a mirror 102, a plurality of masses 104_1 and 104_N, a plurality of masses 106_1 and 106_M, a plurality of actuators 108 and 110, beams 112, 114, 116 and 118, and supports 120 and 122. The values of the indices M and N can be either the same or different.

Beam 112 is coupled with mirror 102 and with mass 104_1. Beam 114 is coupled with mirror 102 and with mass 106_1. Masses 104_1 and 104_N are coupled there between by a plurality of beams (not shown), similar to beam 112. Masses 106_1 and 106_M are coupled there between by a plurality of beams (not shown), similar to beam 112. Beam 116 is coupled with mass 104_N and with support 120. Beam 118 is coupled with mass

106_M and with support 122. Actuator 108 is coupled with mass 104_1. Actuator 110 is coupled with mirror 102. In case mirror 102 is located at a geometric center of scanner 100, mirror 102 can be regarded as a center mass.

Each of beams 112, 114, 116 and 118, and the beams which couple masses 104_1 and 104_N and masses 106_1 and 106_M, is made of a substantially elastic material having a stiffness coefficient k_i. Each of beams 112, 114, 116 and 118, and the beams which couple masses 104_1 and 104_N and masses 106_1 and 106_M, can deflect either linearly or in a planar, spatial or angular fashion.

Each of actuators (i.e., force producing elements) 108 and 110 is a mechanical, electronic, electromechanical, electrostatic, thermodynamic, biomechanical, fluidic element and the like, such as an electromagnet, piezoelectric crystal, electric motor, bi-metallic element, hydraulic motor, fluid impeller, and the like. One or both of actuators 108 and 110 apply forces to either one or both of mass 104_1 and mirror 102, respectively, thereby setting mirror 102, masses 104_1 and 104_N and masses 106_1 and 106_M in motion. The values of masses 104_1 and 104_N, 106_1 and 106_M, the stiffness coefficients k_i of beams 112, 114, 116 and 118, and the beams which couple masses 104_1 and 104_N and masses 106_1 and 106_M, and the waveform of the forces applied by actuators 108 and 110, are selected such that mirror 102 oscillates according to a geometric (i.e., non-trigonometric) waveform, such as a triangular

waveform (e.g., symmetric or asymmetric), non-sinusoidal waveform, square waveform, and the like. Alternatively, either one or both supports can be replaced by an actuator.

Reference is now made to Figure 2, which is a schematic illustration of a five DOF mathematical model of a system similar to the system of Figure 1, generally referenced 150. Mathematical model 150 includes masses 152, 154, 156, 158 and 160, springs 162, 164, 166, 168, 170 and 172, and supports 174 and 176. Each of masses 152 and 160 has a value m_1. Each of masses 154 and 158 has a value m_2. Mass 156 has a value m_3 and is similar to mirror 102 (Figure 1). The spring constant (i.e., stiffness coefficient) of each of springs 162 and 172 is referenced k_1. The spring constant of each of springs 164 and 170 is referenced k_2. The spring constant of each of springs 166 and 168 is referenced k_3.

Spring 162 is coupled with mass 152 and with support 176. Spring 164 is coupled with masses 152 and 154. Spring 166 is coupled with masses 154 and 156. Spring 168 is coupled with masses 156 and 158. Spring 170 is coupled with masses 158 and 160. Spring 172 is coupled with mass 160 and with support 174.

The coordinates of masses 152, 154, 156, 158 and 160 relative to support 176, are referenced q_1, q_2, q_3, q_4, and q_5, respectively. When masses 152, 154, 156, 158 and 160 are set in motion, forces F_1, F_2, F_3, F_4, and F_5, respectively, act thereon.

Since mathematical model 150 is symmetric, the mode shapes (i.e., deformation shapes) thereof can be symmetric (i.e., φ_{sym}) and anti-symmetric (i.e., φ_{asym}), which are expressed by,

$$\phi_{sym} = (\beta_1, \beta_2, \beta_3, \beta_2, \beta_1)^T \qquad (1)$$

and

$$\phi_{asym} = (\alpha_1, \alpha_2, 0, -\alpha_2, -\alpha_1)^T \qquad (2)$$

where α and β are the entries in the eigenvectors or columns of the modal matrix of mathematical model 150.

The equation of motion of masses 152, 154, 156, 158 and 160 is,

$$\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & m_1 \end{bmatrix} q'' + \begin{bmatrix} k_1+k_2 & -k_2 & 0 & 0 & 0 \\ -k_2 & k_2+k_3 & -k_3 & 0 & 0 \\ 0 & -k_3 & k_3+k_3 & -k_3 & 0 \\ 0 & 0 & -k_3 & k_3+k_2 & -k_2 \\ 0 & 0 & 0 & -k_2 & k_2+k_1 \end{bmatrix} q = F \qquad (3)$$

where the units of the variables are as follows:

m_1, m_2, m_3, in Kg

q, in meters

q'', in m/sec^2

k_1, k_2, k_3, in N/m, and

F, in Newtons

The natural frequencies ω_r, $r = 1, 2, 3, 4, 5$, of mathematical model 150 which is described by Equation 3 (i.e., the eigenvalues of Equation 3) and

the eigenvectors φ_r thereof can easily be computed. By solving the following determinants:

$$\left|K-(n\omega_0)^2 M\right|=0 \tag{4}$$

for n = 1,2,3,4,5, k_1, k_2, k_3, m_1, and m_2, can be computed in terms of m_3. Thus,

$$k_1=\frac{25}{7}\omega_0^2 m_3 \tag{5}$$

$$k_2=\frac{45}{7}\omega_0^2 m_3 \tag{6}$$

$$k_3=\frac{15}{2}\omega_0^2 m_3 \tag{7}$$

$$m_1=\frac{10}{7}m_3 \tag{8}$$

$$m_2=\frac{15}{14}m_3 \tag{9}$$

where K and M are the corresponding matrices as defined in Equation 3.

It is noted that mathematical model 150 is a linear model. Equation 3 can be used to describe an angular system similar to mathematical model 150, if the units of the variables in Equation 3 are as follows:

m_1, m_2, m_3, in Kg-μm^2

q, in radians

q'', in rad/sec^2

k_1, k_2, k_3,, in μN-μm/rad, and

Q, in Nm

If the natural frequencies are integer multiples of the resonance frequency ω_0, and m_3 is given, then the following modal matrix, which is independent of masses 152, 154, 156, 158 and 160 and spring constants k_1, k_2 and k_3, is obtained,

$$\phi = \begin{bmatrix} 1 & -3/2 & -9/4 & -1 & 1 \\ 4/3 & -1 & 1 & 2 & -4 \\ 10/7 & 0 & 5/2 & 0 & 6 \\ 4/3 & 1 & 1 & -2 & -4 \\ 1 & 3/2 & -9/4 & 1 & 1 \end{bmatrix} \qquad (10)$$

It is seen that the modal matrix includes both symmetric and anti-symmetric deformation shapes (i.e., the columns of the matrix). In the anti-symmetric mode (i.e., the second and the fourth columns), mass 156 is stationary, as identified by zeros in these two columns. On the other hand, in the symmetric modes (i.e., the first, the third and the fifth columns), masses 152, 154, 156, 158 and 160 are in motion. Ordinarily, the response of mathematical model 150 depends on the excitation parameters. However, in the present case the relative motions of masses 152, 154, 156, 158 and 160 (i.e., the modes shapes of Equation 10), depend only on mass m_3.

It is noted that one or more damping elements (not shown) can be coupled with two respective anchoring points (not shown) of two elements of mathematical model 150, such as masses 152, 154, 156, 158 and 160, springs 162, 164, 166, 168, 170 and 172, supports 174 and 176, and with an actuator (not shown) similar to actuator 108 (Figure 1). The

damping element can be coupled either in series or in parallel with every of these two elements.

For example, the damping element can coupled between support 176 and spring 162 (i.e., in series), between spring 162 and mass 152 (i.e., in series), between the actuator and mass 156 (i.e., in series), between masses 154 and 156 (i.e., in parallel), and the like. If the damping element is incorporated with a system similar to system 100 (Figure 1), the damping element influences the oscillation characteristics of a mirror similar to mirror 102. These damping elements can produce a damping factor which is a function of displacement, velocity, acceleration, impulse, and the like.

Reference is now made to Figures 3, 4A, and 4B. Figure 3 is a schematic illustration of a MEMS based system similar to the system of Figure 1, generally referenced 200. Figure 4A is a schematic illustration of a plot of a frequency response of the mirror of the system of Figure 3, generally referenced 220. Figure 4B is a schematic illustration of a plot of oscillations of the mirror of the system of Figure 3 as a function of time, generally referenced 230.

System 200 includes masses 202, 204, 206 and 208, a mirror 210, a beam 212, supports 214 and 216 and an actuator 218. Beam 212 is coupled between supports 214 and 216. Masses 202, 204, 206 and 208, and mirror 210 are coupled with beam 212. Mirror 210 is located at an approximate center of beam 212. Masses 202 and 204 are located at one

side of mirror 210 and masses 206 and 208 at the other side of mirror 210. Actuator 218 is coupled with mirror 210.

Each of masses 202 and 208 has a value m_1 and a mass moment of inertia j_1. Each of masses 204 and 206 has a value m_2 and a mass moment of inertia j_2. Mirror 210 has a mass m_3 and a mass moment of inertia j_3. The width and length of mass 202 is a_1, and b_1, respectively. The width and length of mass 204 is a_2, and b_2, respectively. The width and length of mass 206 is a_2, and b_2, respectively. The width and length (i.e., geometric characteristics) of mass 208 is a_1, and b_1, respectively. The width and length of mirror 210 is a_3, and b_3, respectively. The cross section of beam 212 is a rectangle having a width t and a height h.

The distance between mass 202 and support 216 is referenced L_1. The distance between masses 202 and 204 is referenced L_2. The distance between mass 204 and mirror 210 is referenced L_3. The distance between mirror 210 and mass 206 is referenced L_3. The distance between masses 206 and 208 is referenced L_2. The distance between mass 208 and support 214 is referenced L_1. The stiffness coefficients of sections of beam 212 having lengths L_1, L_2 and L_3, are referenced k_1, k_2 and k_3, respectively. The footprint of system 200 is a rectangle having a width and a length of approximately 100μm and 2000μm, respectively. In this case, masses 202, 204, 206 and 208, mirror 210 and beam 212 are part of a semiconductor laminate having a substantially uniform and small thickness (i.e., system 200 is a 2.5 dimension system).

Mathematical model 150 (Figure 2) is a relatively simple model, albeit providing only a rough estimate of the required parameters. More accurate results can be obtained by applying a finite element analysis (FEA) to mathematical model 150. Following is an example of the results of a two-dimensional FEA applied to system 200. In this example, actuator 218 applies a variable force F_v to mirror 210, where

$$F_v = A_1\cos(\omega_0 t + \gamma_1) + A_3\cos(3\omega_0 t + \gamma_3) + A_5\cos(5\omega_0 t + \gamma_5) \qquad (11)$$

and where A_1, A_3, and A_5 designate amplitudes, and γ_1, γ_3, and γ_5 designate phase angles. The amplitudes A_1, A_3, and A_5 and phase angles γ_1, γ_3, and γ_5 are selected such that the amplitude of mirror 210 as a function of time, $A(t)$, follows a substantially triangular waveform expressed by,

$$A(t) = \frac{8A_0}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\cos((2n-1)\omega t) = \qquad (12)$$

$$\frac{8A_0}{\pi^2}\left[\frac{\cos(\omega t)}{1^2} + \frac{\cos(3\omega t)}{3^2} + \frac{\cos(5\omega t)}{5^2} + \ldots\right]$$

where A_0 is the desired amplitude and ω is the fundamental frequency of the triangular waveform. With reference to Figure 4A, the resonance frequencies (i.e., the first three harmonics) of system 200 are found to be at ω_0, $3\omega_0$, and $5\omega_0$. Plugging these three harmonics in Equation 12 yields the theoretical oscillations of mirror 210 as a function of time (i.e., curve 222 in Figure 4B). Curve 224 graphically represents the actual amplitude of mirror 210 as a function of time. It is noted that the actual waveform of

mirror 210 (i.e., curve 224) correlates well with the theoretical waveform (i.e., curve 222). It is further noted with reference to Figure 4A, that the maxima of the amplitudes of mirror 210 are located at the respective first three harmonics.

The stiffness coefficients k_1, k_2 and k_3 corresponding to sections L_1, L_2 and L_3, respectively of beam 212, and the mass moments of inertia j_1, j_2 and j_3, are computed according to well known Equations found in Timoshenko S. P. and Goodier J. N., "*Theory of Elasticity*", Third Edition, McGraw-Hill Book Co., 1970. Thus,

$$k_i = \frac{cGh^3t}{L_i} \qquad i = 1,2,3 \tag{13}$$

and,

$$J_i = \frac{a_i b_i s \ \rho(b_i^2 + s^2)}{12} \tag{14}$$

where c is a numerical factor depending on the ratio h/t, G is the shear modulus of beam 212, s is the thickness of each of each of masses 202, 204, 206 and 208, and mirror 210, and ρ is the density of each of masses 202, 204, 206 and 208, and mirror 210. Since system 200 is constructed on a chip, the thickness s of each of masses 202, 204, 206 and 208, and mirror 210 is substantially equal to the thickness t of beam 212. Likewise, the density of each of masses 202, 204, 206 and 208, and mirror 210 is substantially equal to the density of beam 212. Equations 13, and 14 are computed while neglecting the warping function correction for estimating

the torsional spring rate, as shown in Basler K., and Kollbrunner C. F., "*Torsion in Structures*", Springer Verlag, New York, 1969.

As shown in Equations 13, and 14, the stiffness coefficient k depends on h, t and L, while the mass moment of inertia depends on a, b and s. Due to redundancy of the physical dimensions, some of the parameters of system 200 have to be assumed beforehand. Assuming the following values and substituting them in equations 13 and 14,

$j_3 = 1.8238 \times 10^{-5}$ Kg-μm^2 $h = 10$μm

$t = s = 15$μm $b_1 = b_2 = 600$μm

$b_3 = 500$μm

$\rho = 2.332\text{e-}15 \times 10^{-15}$ Kg/μm^3, and

$G = 8.831\text{E}4 \times 10^4$ Kg/μm-s^2

the gaps between masses 202, 204, 206 and 208, mirror 210, and supports 214 and 216, and the width of masses 202, 204, 206 and 208, mirror 210, are calculated as follows:

$L_1 = 44.9$μm

$L_2 = 24.9$μm

$L_3 = 21.4$μm

$a_1 = 413.5$μm

$a_2 = 210.2$μm, and

$a_3 = 500$μm

Assuming a first resonance frequency of $\omega_0 = 15$ kHz for system 200, and solving Equations 5, 6, 7, 8 and 9, the following values for the stiffness coefficients k_1, k_2, k_3, corresponding to portions L_1, L_2, and L_3, respectively, of beam 212, m_1 for mass moments of inertia of masses 202 and 208 and m_2, for mass moments of inertia of masses 204 and 206 are obtained:

$k_1 = 0.5786$ N-µm/rad

$k_2 = 1.041$ N-µm/rad

$k_3 = 1.215$ N-µm/rad

$m_1 = 2.6054 \times 10^{-4}$ Kg-µm^2, and

$m_2 = 1.9541 \times 10^{-4}$ Kg-µm^2

where the mass m_3 is replaced by the mass moment of inertia j_3.

Reference is now made to Figure 5, which is a schematic illustration of a scanner, generally referenced 240, constructed and operative in accordance with another embodiment of the disclosed technique. Scanner 240 includes a mirror 242, beams 244 and 246, supports 248 and 250, an actuator 252 and a controller 254. Actuator 252 includes electrodes 256 and 258.

Beam 244 is coupled with mirror 242 and with support 250. Beam 246 is coupled with mirror 242 and with support 248. Electrodes 256 and 258 are located on top of mirror 242. Electrodes 256 and 258 are coupled with controller 254. Mirror 242 is electrically grounded.

Controller 254 applies a voltage V_1 to electrode 256, where

$$V_1 = V_0 + A_1\cos(\omega_0 t + \gamma_1) + A_3\cos(3\omega_0 t + \gamma_3) + A_5\cos(5\omega_0 t + \gamma_5) \qquad (15)$$

and a voltage V_2 to electrode 258, where

$$V_2 = V_0 - \left[A_1\cos(\omega_0 t + \gamma_1) + A_3\cos(3\omega_0 t + \gamma_3) + A_5\cos(5\omega_0 t + \gamma_5)\right] \qquad (16)$$

where V_0 is a bias voltage, A_1, A_3, and A_5 designate amplitudes, and where γ_1, γ_3, and γ_5 designate phase angles. Mirror 242 oscillates relative to supports 248 and 250, in directions designated by arrows 260 and 262, in a substantially triangular waveform expressed by Equation 12 herein above.

Reference is now made to Figures 6A and 6B. Figure 6A is a schematic illustration of a packaged device generally referenced 280, including a plurality of the scanners of Figure 1, constructed and operative in accordance with a further embodiment of the disclosed technique. Figure 6B is a schematic illustration of a broken section of a scanning MEMS of the packaged device of Figure 6A.

With reference to Figure 6A, packaged device 280 includes a housing 282, a plurality of electrical contacts 284, an integrated circuit (IC) 286, and a scanning MEMS 288. Each of electric contacts 284 includes a pin 290 which protrudes from a bottom side 292 of packaged device 280. Packaged device 280 can be mounted on another device (not shown) and make electric contact with this device, by pins 290. Scanning MEMS 288 is located on top of IC 286 such that electric terminals (not shown) of scanning MEMS 288 are connected to corresponding electric terminals of

IC 286. Each of electric terminals 294 of IC 286 is connected to the respective electric contact 284 by a bonding wire 296.

With reference to Figure 6B, scanning MEMS 288 includes a substrate 298, a protection layer 300 and an optically transparent layer 302. Substrate 298 can be made of a semiconductor, such as silicon, gallium arsenide, and the like. Substrate 298 includes a plurality of scanners 304 similar to scanner 100 (Figure 1). Light can enter and exit each of scanning MEMS 288 through respective windows 306. Electric terminals (not shown) on a bottom side 308 of substrate 298 are connected to respective electric terminals (not shown) on a top side 310 of IC 286.

According to a further embodiment of the disclosed technique, the system is constructed on two or three dimensions where the actuators and masses are spread across a plane or a volume, thereby producing a waveform which can be measured in two or three spatial dimensions.

It will be appreciated by persons skilled in the art that the disclosed technique is not limited to what has been particularly shown and described hereinabove. Rather the scope of the disclosed technique is defined only by the claims, which follow.